Supplementary Information
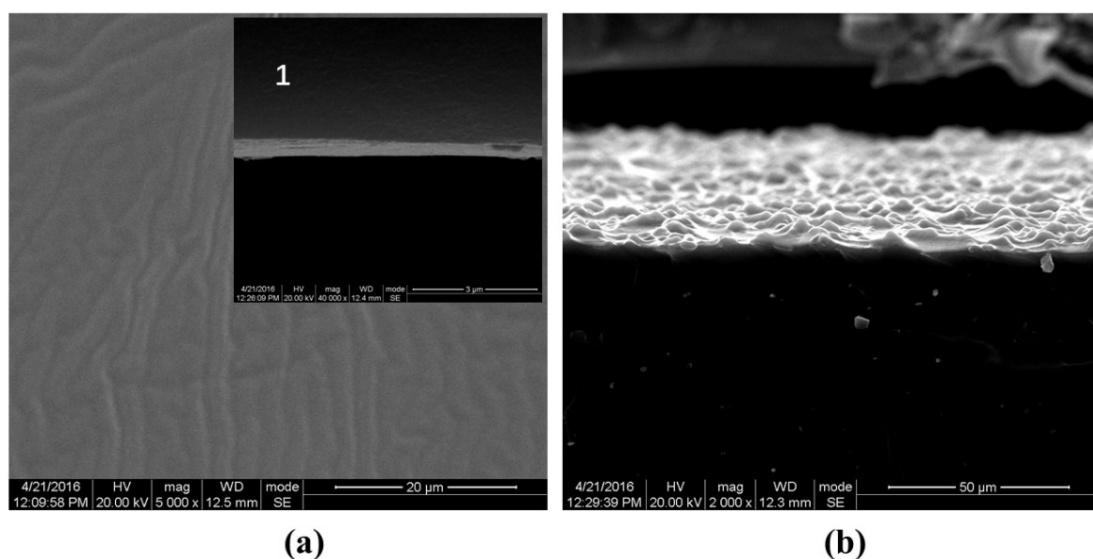

(a) (b)

Fig. S1 SEM images of PDMS films prepared. (a) Top view of flat PDMS film prepared on flat glass sheet, and the inset 1 is the cross-sectional view. (b) Cross-sectional view of micro-patterned PDMS film prepared on ground glass sheet.
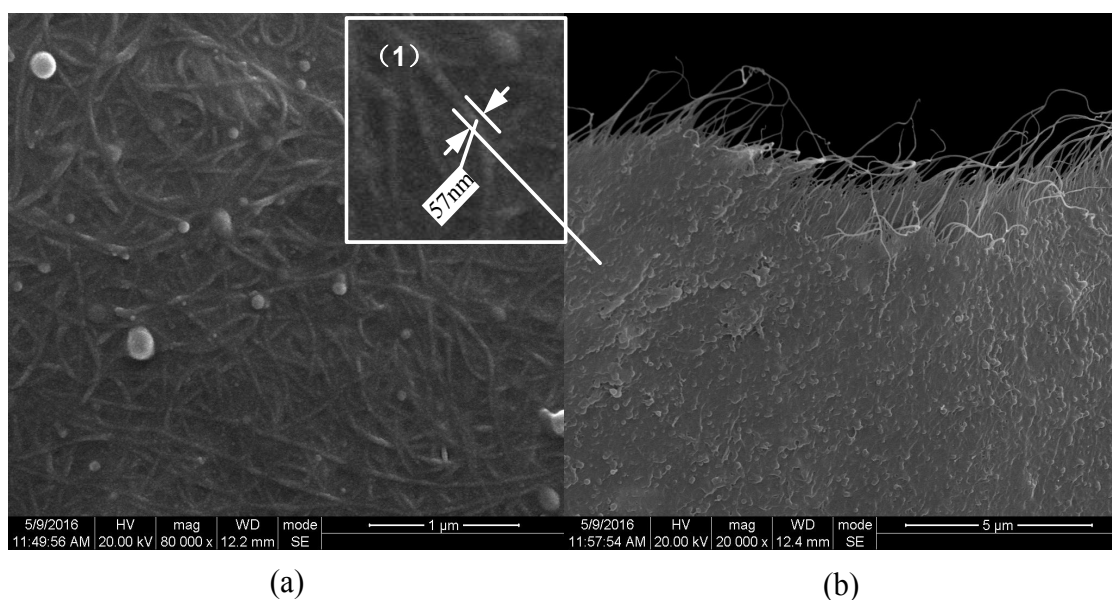

(a) (b)

Fig. S2 SEM images of CNT films prepared by filtration method. (a) Top view of CNT film, and the Inset 1 shows the details of the CNT film.
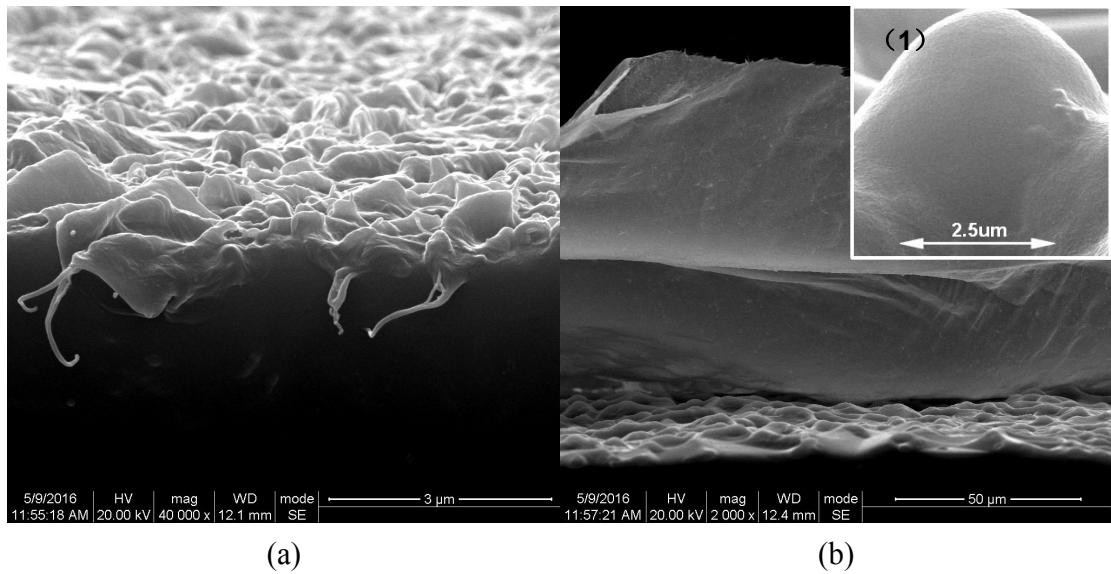
(b) Cross sectional view of CNT film.

(a)   (b)

Fig. S3 Cross sectional SEM images of CNT/PDMS films. (a) The PDMS used is flat PDMS film, (b) The PDMS used is patterned PDMS film. Inset 1 shows the details of papillary microstructural film's edge.
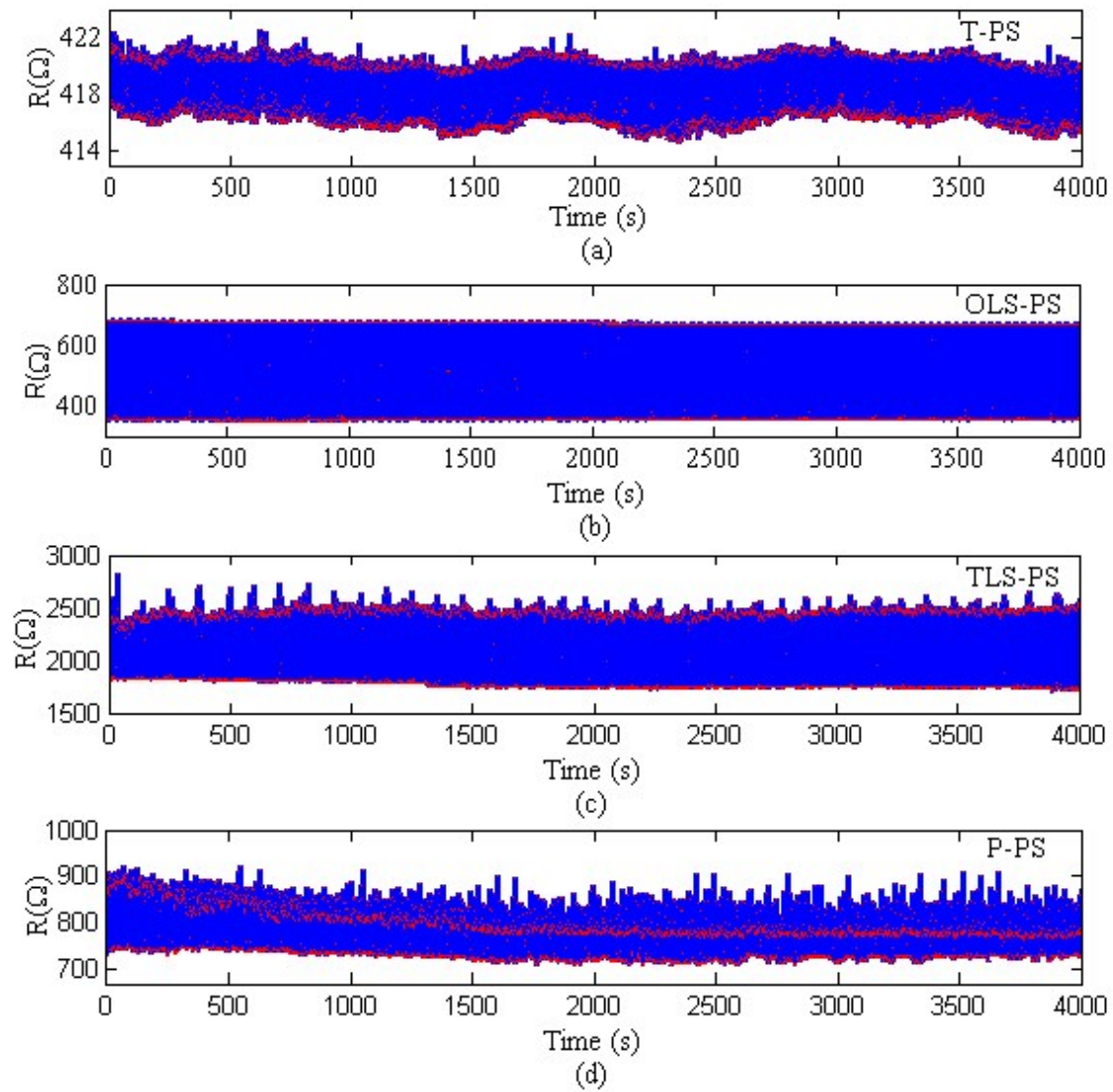
Fig. S4 Stability response diagram of four kinds of flexible pressure sensors. (a) Stability test response diagram of T-PS. (b) Stability test response diagram of OLS-PS. (c) Stability test response diagram of TLS-PS. (d) Stability test response diagram of P-PS.
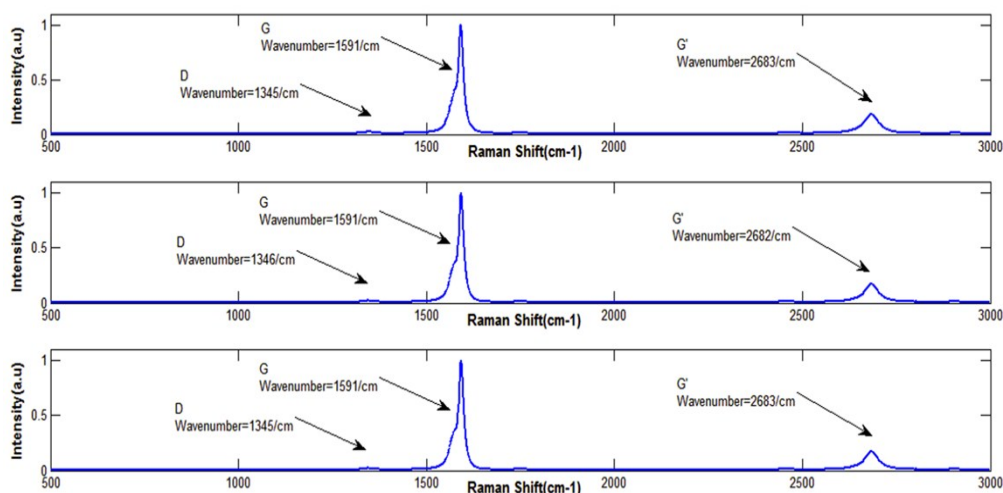
Fig. S5 Raman spectra of three sampling points on the CNTs film, which confirmed the existence of the component of CNTs. The characteristic peaks are annotated by the arrow with the annotation of wavenumber of the Raman Shift. According to the results, the characteristic peak of the D band is around 1345cm⁻¹, the characteristic peak of the G band is around 1591cm⁻¹ and the characteristic peak of the G' band is around 2683cm⁻¹. The results conform with the data of other reports.

TABLE S1 Characteristic Raman spectra peaks of CNTs

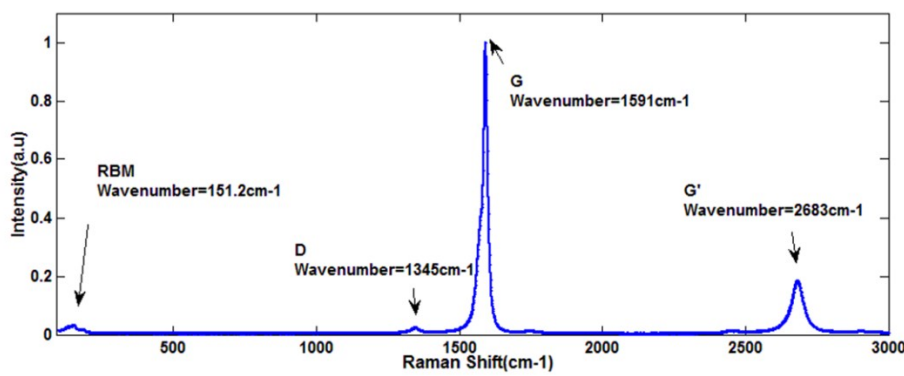| Characteristic peak	CNT standard wavenumber reported [ref.1,2] (cm⁻¹)	CNT standard wavenumber of our samples (cm⁻¹)
D Band	1250~1450	1345
G Band	1500~1605	1591
G' Band	2500~2700	2683
RBM Band	160~300	151.2

Fig. S6 The enlarged Raman spectrum at a single test point. The enlarged diagram can show more details about the characteristic peaks of the Raman shift. There are 4 characteristic peaks in the Raman spectrum. The wavenumber of the characteristic peak in the RBM band is around 151.2 cm^{-1}, that in the D band is around 1345 cm^{-1}, that in the G band is around 1591 cm^{-1} and that in the G' band is around 2683 cm^{-1}.

TABLE S2 The sensitivities of different structure pressure sensors in different regions

Type	S1[a](kPa^{-1})	S2[b](kPa^{-1})
T-PS	10.69	0.36
OLS-PS	58.90	0.66
TLS-PS	33.40	0.25
P-PS	4.00	0.14

[a]S1 is the sensitivity of the pressure sensor in liner region 1
[b]S2 is the sensitivity of the pressure sensor in liner region 2

(To compare sensitivities of different pressure sensor, Table S2 shows the sensitivities of different pressure sensors in different regions. The OLS-PS has the largest sensitivity (58.9 kPa^{-1} in 1-5 Pa; 0.66 kPa^{-1} in 5-100 Pa) in both the low pressure region and the high pressure region, among the different sensors. And the sensitivity of TLS-PS (33.40kPa^{-1} in 5-10 Pa; 0.25 kPa^{-1} in 10-100 Pa) is higher than the sensitivity of the T-PS, but lower than the sensitivity of the OLS-PS.)
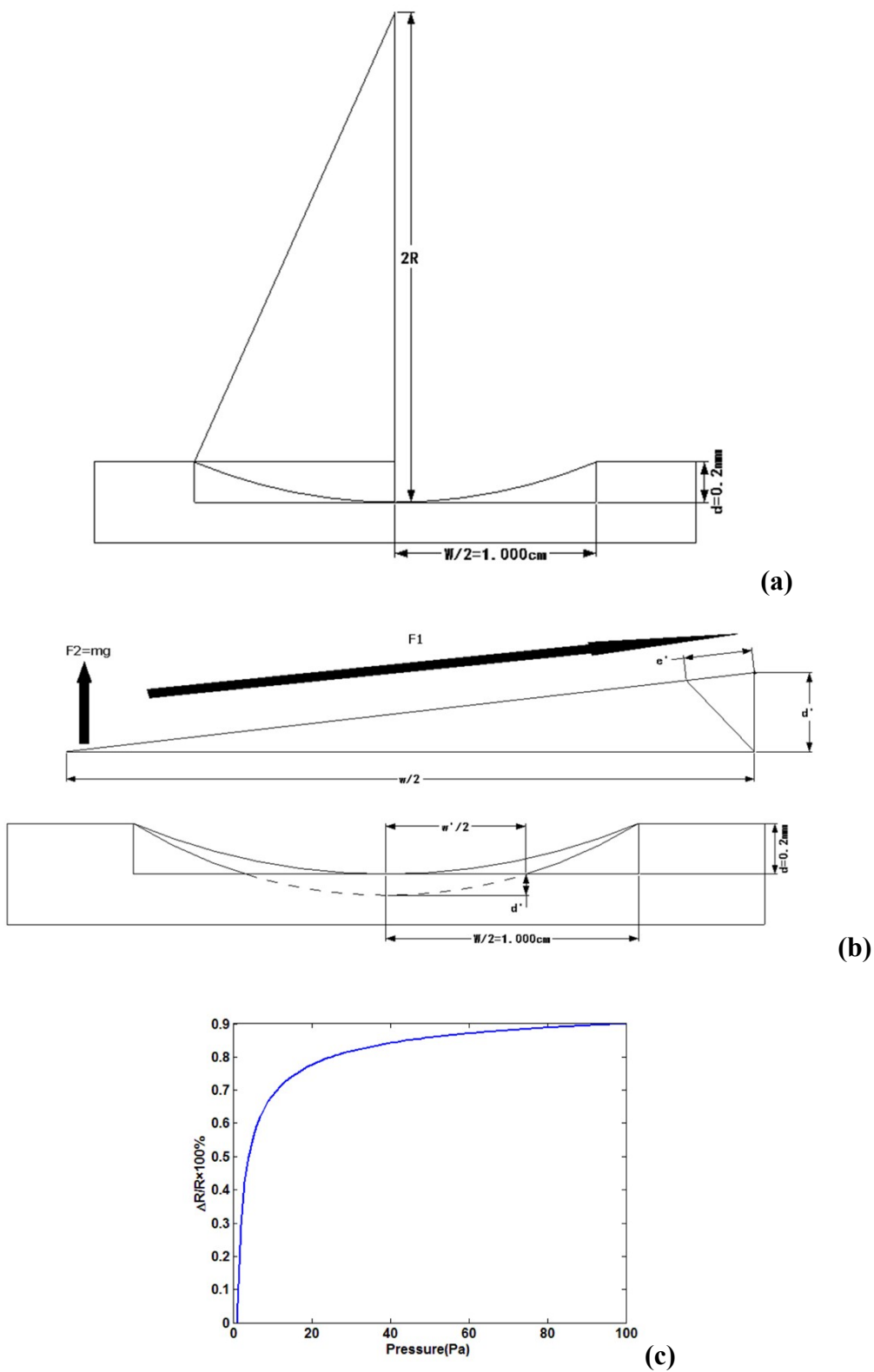
(a)

(b)

(c)

Fig. S7 An ideal model analysis for the air gap flexible pressure sensor.

(a),(b) showed the cross-sectional analysis of the pressure sensor, and (c)showed the pressure sensor's response in simulation result.

The detailed analysis of above Fig. 7 is as follows:

Many factors (eg. shape of the PDMS film surface and contact resistance per area of the pressure sensor) cannot be described by mathematical model, it's hard to build up the precise model for pressure sensor. Here, an ideal model of air gap flexible pressure sensor is established, and a tentative analysis is made.

Fig. 7(a) showed the cross-sectional views of the pressure sensor. The upper conductive film will sag, leading to form a cylindrical surface. The radius of the cylindrical surface is defined as R. The thickness of the PDMS strips is defined as d. The width of air gap in the pressure sensor is defined as w. We can use the length of upper conducting film to minus the double value of the width of the PDMS strips to get the width of the air gap.

From the structure we can calculate the radius R by the formula below.

$$\frac{2R-d}{w/2} = \frac{w/2}{d} \tag{1}$$

To get more information about the sensing mechanism of the pressure sensor, the cross-sectional views of pressure sensor under the applied pressure is shown in the followed Fig. 7(b). The F1 denotes the force generated by the upper PDMS film. The F2 denotes the vertical component of the F1. The e' denotes the length of the deformation along the PDMS film. The d' denotes the vertical component of the deformation e'. The w' denotes the width of the contact area between the upper film and bottom film. Based on the mechanical relationship and geometrical relationship, we can obtain the formulas as below.

According to the geometrical relationship, we can obtain the scale relation as follows.

$$d' << w/2, \quad e' << w/2 \tag{2}$$

$$e' = d' \times d'/(w/2) \tag{3}$$

According to the structure of the pressure sensor and spatial force analysis, the expressions of different forces is listed as followed.

$$F2 = P \times S1 \tag{4}$$

$$F1 = Y \times S2 \times (\frac{e'}{w/2}) = F2 \times \frac{w/2}{d'} \tag{5}$$

In the formula (4), P is the test pressure applied on the pressure sensor. And S1 is the area of the upper flexible conductive film, which can be calculated by the formula as follow (the size of the pressure sensor is 3×3 cm).

$$S1 = 3cm \times 3cm = 0.0009m^2 \tag{6}$$

In the formula (5), the S2 is the cross-sectional area of the upper flexible conductive film and the Y denotes the Young's modulus of PDMS.

$$S2 = 3cm \times d = 6 \times 10^{-6} m^2 \tag{7}$$

According the formulas listed above, the mathematical expression of the relation between the P and d' can be deduced as follow.

$$d' = \sqrt[3]{P \times S1 \times (w/2)^3 / (S2 \times Y)} \tag{8}$$

For analyzing the sensing mechanism of the pressure sensor, we need discuss the relation between the deformation d' and the resistance (denoted as Rs) of the pressure sensor. We can get the expression of the pressure sensor's as follow.

$$Rs = K / S3 \tag{9}$$

In the formula, Rs denotes the resistance of the pressure sensor. The S3 denotes the contact area between the upper flexible conductive film and the bottom flexible conductive film. The K is a constant which is determined by the property of the pressure sensor. Because the resistance of pressure sensor cannot be described by the ideal resistance model. So we cannot use the length and the volume resistivity to describe the property of the pressure sensor. Then we just use the K to represent the property of pressure sensor. The w' is the width of the contact area and the length of the contact area equals to the length of the pressure sensor. We can get the expression of the contact area as below.

$$S3 = w' \times 3cm \tag{10}$$

According to the structure of pressure sensor shown in the Fig. 7(a), we can get the relation between the deformation d' and the w'.

$$(w'/2)^2 + (R - d')^2 = R^2 \tag{11}$$

$$w' = 2 \times \sqrt{2 \times R \times d' - d'^2} \tag{12}$$

So we can calculate the resistance of the pressure sensor under a fixed applied pressure based on the formula listed below.

$$Rs = \frac{K}{2 \times 0.03m \times \sqrt{2 \times R \times d' - d'^2}} \tag{13}$$

According the formula (13) and formula (8), we can obtain the relation of the applied pressure and the resistance of the pressure sensor as follow.

$$Rs = \frac{K}{2 \times 0.03m \times \sqrt{2 \times R \times \sqrt[3]{P \times S1 \times (w/2)^3 / (S2 \times Y)} - \left(\sqrt[3]{P \times S1 \times (w/2)^3 / (S2 \times Y)}\right)^2}} \tag{14}$$

It's hard to calculate the precise resistance value of the pressure sensor. So we use the normalized resistance to evaluate the performance of the pressure sensor. The normalized resistance is defined as follow. The p_0 (1 pa) denotes the initial applied pressure. The $Rs(p_0)$ represents the initial resistance value of the pressure sensor. The p denotes the test pressure applied on the pressure sensor. The Rs(p) represents the resistance value of the pressure sensor under the fixed test pressure. So the $R_{response}$ means the relative change rate of the pressure sensor under a fixed test pressure.

$$R_{response} = \frac{Rs(p_0) - Rs(p)}{Rs(p_0)} \times 100\% \tag{15}$$

According the formula (15) and formula (14), the expression of the normalized resistance versus pressure can be obtained as follow.

$$R_{response} =$$

$$(Rs(p_0) - \frac{K}{2 \times 0.03m \times \sqrt{2 \times R \times \sqrt[3]{P \times S1 \times (w/2)^3 / (S2 \times Y)} - \left(\sqrt[3]{P \times S1 \times (w/2)^3 / (S2 \times Y)}\right)^2}}) / Rs(p_0)$$

(16)

Based on the formula (16), we can simulate the normalized resistance of the pressure sensor under a fixed test pressure to obtain the response curve. The diagram of the pressure sensor's response in simulation is shown in the Fig. 7(c). In the result, we can find that there are 2 linear regions in the response diagram. The linear region with high slope is in the low pressure region (0~10 pa) and the linear region with low slope is in the high pressure region (10~100 Pa).

The simulation results above basically match our testing results. This simple analytical model incorporates the key mechanical properties of the PDMS, the geometry of the sensor and the applied pressure. This model could basically evaluate the contact condition of the CNT electrodes under various pressure, and can illustrate the two linear regions Moreover, this model is a kind of ideal model without considering the detail of the pressure sensor.

To keep the article brief and intact, we think that it is better to avoid adding the detail theoretical analysis in the manuscript.